Observation of thermal-induced optical guiding and bistability in a mid-IR continuous-wave, singly resonant optical parametric oscillator

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We report the observation of thermal-induced optical guiding and bistability in a mid-IR cw, singly resonant optical parametric oscillator (SRO) at ~3.2 μm. The SRO employs a MgO:PPLN crystal as the gain medium and a 1-nm-linewidth Yb-fiber laser at 1.064 μm as the pump source. As soon as the pump power reaches the thermal guiding threshold at 16.5 W, the SRO shows a step increase in the parametric efficiency by a factor of 2.5. At 25 W pump power, the SRO generated 5.3 and 1.2 W at 1.58 and 3.23 μm, respectively, with single-longitudinal-mode performance for the 3.23 μm radiation. © 2008 Optical Society of America

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Wavelength-tunable, narrow-line, cw laser sources in the mid-IR region are desirable for such applications as sensing and monitoring environmental or biological chemicals. To date, most mid-IR optical parametric oscillators were designed to resonate a near-IR signal wave and generate a mid-IR idler wave through difference frequency generation between the pump and signal waves [1]. This scheme requires a single-frequency pump to generate single-frequency mid-IR radiation [2]. Direct oscillation of a mid-IR component in an optical parametric oscillator has long been thought to be difficult and inefficient, owing to relatively fast diffraction and large absorption at mid-IR wavelengths [3]. The anticipated high pump threshold and low efficiency have rendered a mid-IR singly resonant optical parametric oscillator (SRO) relatively unexplored. In this Letter, we chose to resonate the mid-IR component in an SRO and demonstrated a drastic increase of parametric efficiency at the onset of thermal guiding. The adverse effect of the mid-IR absorption in the conventional view is surprisingly helpful in forming a thermal waveguide in the SRO and increasing the mode overlap among mixing waves. Hence we are able to show in the following an efficient single-longitudinal-mode cw mid-IR SRO at ~3.2 μm pumped by an economical broadband Yb-fiber laser at 1.064 μm.

In this Letter, a 5 mol. %-doped MgO:PPLN crystal with a domain period of 30.7 μm (made by HC Photonics) was used as the parametric gain medium of the ~3.2 μm SRO. The crystal is 50 mm long in x, 6 mm wide in y, and 1 mm thick in z. The SRO configuration of our work is the same as the bow-tie ring resonator shown in [2], consisting of two curved mirrors with a 100 mm radius of curvature and two flat mirrors. The four reflecting mirrors are made of infrared-grade fused silica. All four cavity mirrors have >99.9% reflectance over a wavelength range from 3200 to 3400 nm and >97% transmittance over a wavelength range from 1550 to 1650 nm and at the pump wavelength. The PPLN crystal was installed in an oven between the two curved mirrors so that the pump beam enters at the first curved mirror, traverses the PPLN crystal, and exits at the second curved mirror. The mid-IR resonant wave is deflected to the two flat mirrors by the second curved mirror and fed back to the first one to form a unidirectional optical path. The total cavity length of the ring SRO was 500 mm, and the mode radius at the center of the PPLN crystal was 100 μm.

The pump laser is a linearly polarized Yb-fiber laser (IPG YLM-25-LP) at 1064 nm, producing maximum 25 W cw power in a 1 nm or 265 GHz spectral width. The pump beam was polarized along the crystallographic z direction of the MgO:PPLN crystal and was mode matched to the SRO cavity by using a 150 mm focal-length lens. The waist radius of the pump beam at the center of the crystal was 90 μm. The 30.7 μm period of the MgO:PPLN crystal permits the first-order quasi-phase matching of the pump, signal, and idler waves at 1.064, 1.57, and 3.3 μm, respectively, at a crystal temperature of 50°C. The two end apertures of the PPLN crystal were optically polished and coated with 0.5, 0.2, and 14% reflectances at the pump, idler, and signal wavelengths, respectively.

Figure 1 shows the measured signal power versus the pump power. At 25 W pump power, we obtained 7.4 W signal power at 1.57 μm exiting the second curved mirror and 50 mW idler power at 3.3 μm exiting each of the four cavity mirrors. The filled and open dots denote the output signal powers when the pump power was increased from 0 to 25 W and back to 0 W, respectively. Owing to the diffraction and absorption loss of the 3.3 μm resonant wave in the MgO:PPLN crystal, the ~9 W pump threshold of this SRO is approximately 2.5 −9 times that of a similar SRO resonating at the signal wavelength [1,4]. Fol-

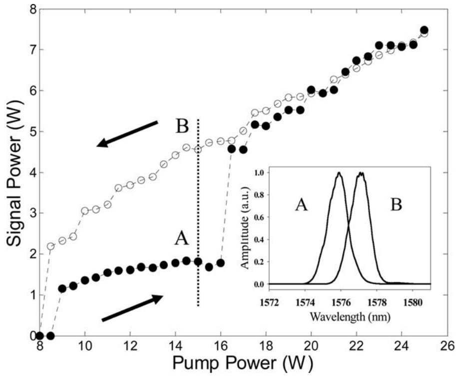

Fig. 1. Measured output signal power versus the pump power of the SRO. The filled and open dots denote the measured signal power when the pump power was varied from 0 to 25 W and back to 0 W, respectively. The inset shows a shift in the signal wavelength for the two bistability states A and B at 15 W pump power.

lowing the technique in [4], we measured 2.45% absorption at 3.3 μm in the 5-cm-long MgO:PPLN crystal, which is about 6 times the absorption near the signal wavelength. Taking into account all the losses at 3.3 μm in the SRO, we found a theoretical threshold power of ~5 W in the ideal Gaussian-beam limit [3]. The thermally induced beam distortion, to be discussed below, might account for the increased oscillation threshold in the experiment.

It is interesting to see a step increase of the signal power from 1.7 to 4.2 W when the pump power is gradually increased to about 16.5 W. Decreasing the pump power does not trace back the SRO signal power measured during the increasing phase of the pump power, as indicated by the arrows in Fig. 1. The SRO has two stable states between 8.5 and 16.5 W pump powers, labeled as State A and State B in the plot. Compared with the low-power state (State A), the high-power state (State B) has a much higher conversion efficiency and a slightly lower pump threshold. The inset shows the signal spectra of the two states at 15 W pump power and 65°C crystal temperature. The linewidths of these two signal waves are both 1.3 nm or 160 GHz. The central wavelength of the high-power state is 2 nm longer than that of the low-power state. This wavelength separation can be explained by a 4°C temperature increase in the MgO:PPLN crystal for the high-power state. We also observed heating of the crystal when we operated the SRO with the crystal oven set at room temperature. Therefore the hysteresis loop in Fig. 1 is associated with thermally induced optical bistability.

To find out the time constant of this thermal process, we modulated the pump laser intensity with a 50% duty cycle by using an optical chopper. The modulation rate of our chopper can be continuously varied up to 400 Hz. At 20 W pump power, the high-power state can only be obtained for a modulation frequency higher than 200 Hz. For pump power between 10 and 16 W, the high-power state quickly shifted to the low-power state, even at the 400 Hz modulation rate. This indicates that turning off the pump laser over a period of a few milliseconds can terminate the bistability of the SRO, which is consistent with the time constant for most thermal-induced effects in a laser material.

The absorption-induced heating in a MgO:PPLN crystal has been observed in the past for a SRO [4] with a resonant wavelength between 1.6 and 1.9 μm. The crystal heating was found to degrade the beam quality of the mixing waves by the thermal lensing effect. For our SRO, the crystal heating is even more profound owing to the circulating mid-IR wave in the cavity. However, this increased crystal heating is sufficient to turn the disadvantageous beam distortion into the advantageous optical guiding in our SRO. To observe the transition, we installed a silicon CCD camera at 60 cm from the center of the PPLN crystal in the downstream pump direction. Figures 2(a)–2(c) show the recorded far-field profiles of the pump beam (a) at the low-power state without SRO in operation and (b) with SRO in operation, and (c) at the high power state with SRO in operation. Figure 2(a) was recorded by inserting a piece of paper into the SRO to terminate the oscillation at the low-power state. As the pump power just exceeds the SRO threshold, the mode diameter of the pump laser in Fig. 2(b) is increased by three times compared with that of the pump beam without SRO in operation. The pump-beam diameter in Fig. 2(b) was found to vary slightly with the pump power. This simple test confirms the effect of thermal lensing in the PPLN crystal due to the intracavity mid-IR power. The thermal lensing at the low-power state causes the mode mismatch among mixing waves and increases the oscillation threshold, as also pointed out by Moore's previous simulation study [5]. As soon as the pump power was increase to the thermal guiding threshold at 16.5 W, the pump-beam diameter was suddenly reduced, as Fig. 2(c) shows. Above the guiding threshold, the mode profile in Fig. 2(c) was relatively insensitive to the pump power. The thermal guiding in the PPLN crystal can greatly enhance the mode overlap among mixing waves and thus increase the parametric conversion efficiency.

Figure 3 shows the pump depletion versus the pump power and the number of times above the threshold. The oscillation thresholds for the two bistability states are different, so to be conservative, the higher of the two values (9 W) was used to calculate the number of times above the threshold. After the pump power reached the oscillation threshold, the pump depletion of the low-power state increased to about 25% but decreased to 20% at 1.9 times above threshold. However, the pump depletion increased to and clamped at 50%–60% after the pump power ex-

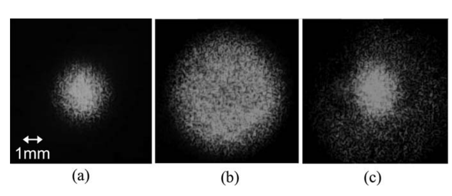

Fig. 2. Far-field profiles of the pump beam (a) at the low-power state without SRO in operation and (b) with SRO in operation, and (c) at the high-power state with SRO in operation.

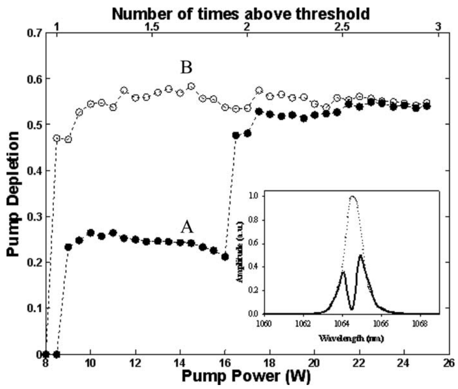

Fig. 3. Pump depletion versus the pump power and the number of times above the threshold. The labels A (filled dots) and B (open dots) denote the two bistability states. The pump depletion is clamped at 50%–60% when the pump power exceeds the thermal guiding threshold at 16.5 W. The inset shows spectral hole burning in the depleted pump, which explains the clamped pump depletion.

ceeded the thermal-guiding threshold or 2 times above the oscillation threshold. Owing to the thermal guiding, 50%–60% pump depletion was maintained over almost the whole range of the high-power state (State B). The clamped pump depletion of the SRO in this study is fairly different from the monotonically increased one previously reported for the narrow-line (~2.2 GHz and ~5 kHz) pumped ring SROs resonating the 1.5 μm signal wave [1,2]. The inset in Fig. 3 shows the measured power spectrum of the depleted pump laser at 20 W input power. The spectral hole burning in the depleted pump indicates that the broad linewidth of the Yb-fiber laser, 1 nm or 265 GHz, is the main cause of the clamped pump depletion. From the depleted pump spectrum, the optimal pump-laser linewidth for the SRO should be within ~60% of the 1 nm pump linewidth. This is consistent with the 160 GHz signal linewidth shown in the inset of Fig. 1 and is also consistent with the calculated phase-matching bandwidth of the SRO using the 5 cm PPLN crystal.

Watt-level power at the idler wavelength could be useful for various applications requiring high average power in the mid-IR spectrum. We replaced one of the two flat reflectors with a mid-IR output coupler with a flat surface. The output coupling varied from 1% to 6% when we tuned the SRO idler wavelength from 3215 to 3245 nm by varying the crystal temperature from 95°C to 83°C. Figure 4 shows the measured signal power exiting the second curved mirror and the idler power exiting the output coupler as a function of the output coupling when the pump power was fixed at 25 W and the crystal temperature was varied. When performing the measurement, we first raised the crystal temperature to 110°C, the phase-matching temperature corresponding to ~0.1% output coupling at the idler wavelength, and kept the SRO at the high-power state with 25 W pump power; we then gradually decreased the crystal

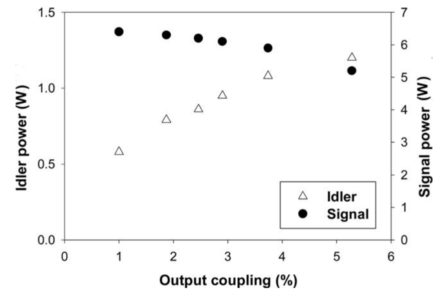

Fig. 4. Signal and idler output power as a function of output coupling of the idler wave when the pump power was fixed at 25 W and the crystal temperature was varied from 95°C to 83°C.

temperature to 83°C to complete the measurement at the high-power state. The maximum idler power of 1.2 W was measured with 5.3% output coupling. At the maximum idler output power, we measured a single-longitudinal-mode linewidth of ~5 MHz for the idler wave by using a scanning confocal Fabry–Perot spectrometer (free spectral range = 0.75 GHz, finesse >600). Although our crystal oven can stabilize the PPLN temperature only down to ±0.1°C or the signal frequency down to ±~6 GHz, we observed thermal frequency locking [6] during the spectral measurement.

In summary, we have reported the first observation of thermally induced optical guiding and bistability in an optical parametric oscillator. When the pump power reached a threshold value of 16.5 W, the slight absorption of the 3 μm resonant wave in the MgO:PPLN turned disadvantageous thermal lensing into advantageous thermal guiding in the SRO. At the thermal guiding threshold, we observed a step increase in the parametric efficiency by a factor of 2.5. To the best of our knowledge, we have also demonstrated a cw SRO resonating at the mid-IR wavelength with a single-longitudinal-mode output by using a fairly broadband pump laser at 1 μm. The measured spectral hole burning in the depleted pump suggests the possibility of further increasing the parametric efficiency with a pump linewidth less than 160 GHz.

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References

1. W. R. Bosenberg, A. Drobshoff, J. I. Alexander, L. E. Myers, and R. L. Byer, Opt. Lett. **21**, 1336 (1996).
2. M. M. J. W. van Herpen, S. T. L. Hekkert, S. E. Bisson, and F. J. M. Harren, Opt. Lett. **27**, 640 (2002).
3. S. Guha, Appl. Phys. B **66**, 663 (1998).
4. A. Henderson and R. Stafford, Appl. Phys. B **85**, 181 (2006).
5. R. O. Moore, G. Biondini, and W. L. Kath, J. Opt. Soc. Am. B **19**, 802 (2002).
6. M. Vainio, J. Peltola, S. Persijn, F. J. M. Harren, and L. Halonen, Opt. Express **16**, 11141 (2008).